Mars Exploration Rover Engineering Cameras

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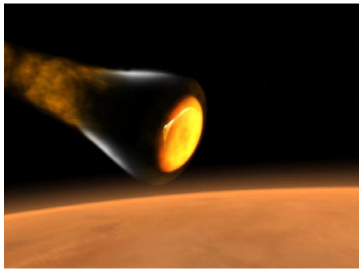
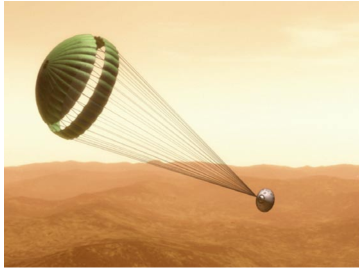
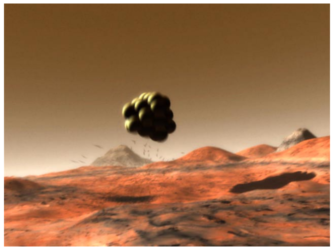
Mars Exploration Rover 2003 (MER) Mission

- **Mars exploration a high NASA priority**
  - MGS mission images showed evidence substantial past liquid water on Mars
  - Since water is considered essential to life—past or present life possible
- **Two scientific spacecraft**
  - Delta 2 boosters
  - Two different near equatorial locations on Mars
  - June and July 2003 launches
- **Primary goal—obtain knowledge of ancient water and climate of Mars**
- **Mars capture and landing by aero shell, parachute and airbags**



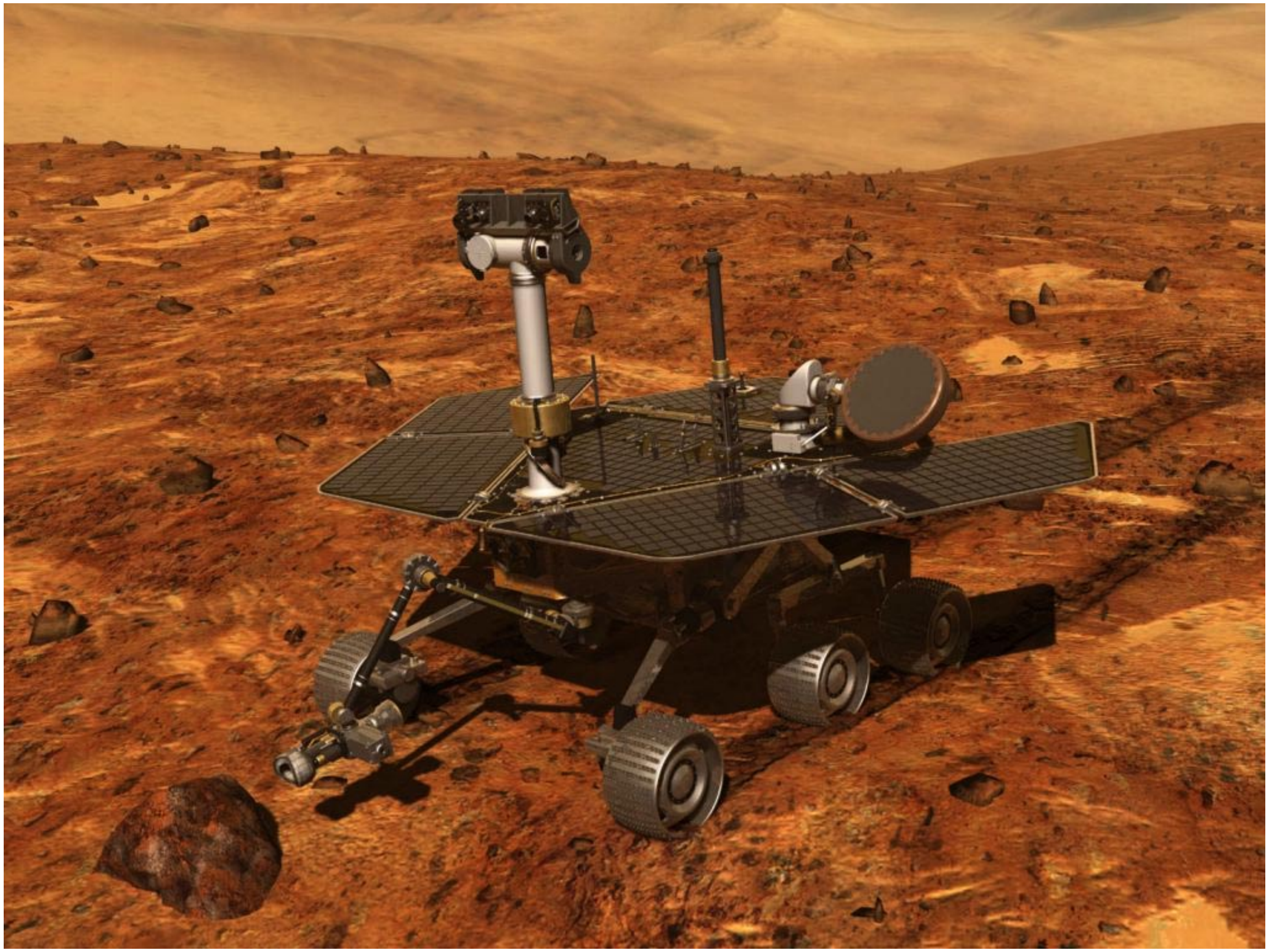




MER Rovers

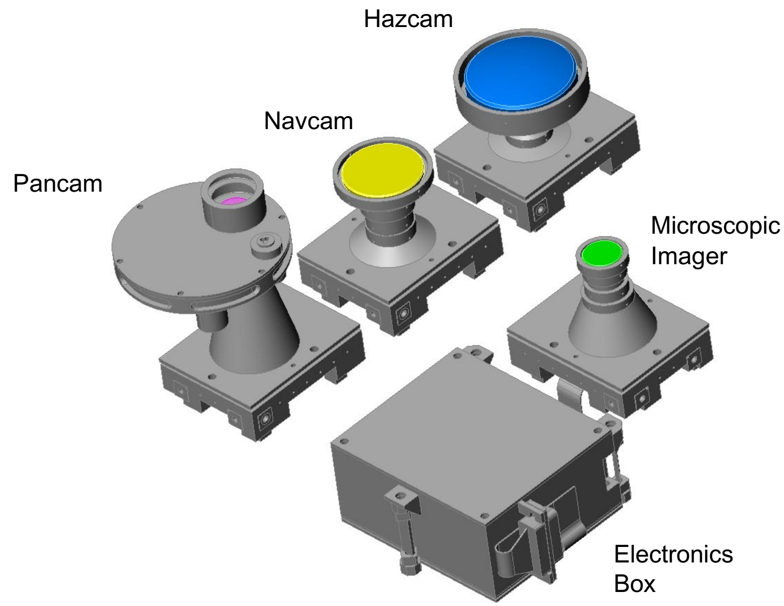
- Each spacecraft will carry one rover
- Six wheels
- 155 kg mass
- 90 Martian day lifetime—limited by seasonal temperature drop and dust obscuration of the solar panels
- Design travel distance of up to 100 meters/day
- Independent of lander
- Direct communications with earth
- Operation by Earth-based target selection and on-board autonomous navigation using imaging data
- Rover operational from about 10:00 to 15:00 Martian time when sufficient solar power available

MER Rover on Mars Visualization



MER Cameras

- Nine cameras of four types
  - One stereo pair of Panoramic Cameras (Pancams)
  - One Microscopic Imager (MI)
  - One stereo pair of Navigation Cameras (Navcams)
  - Two stereo pairs of Hazard Avoidance Cameras (Hazcams)
- Each camera type has a unique design optical assembly
- Typical mass 350 g
- Power consumption less than 3 W



MER Cameras (cont.)

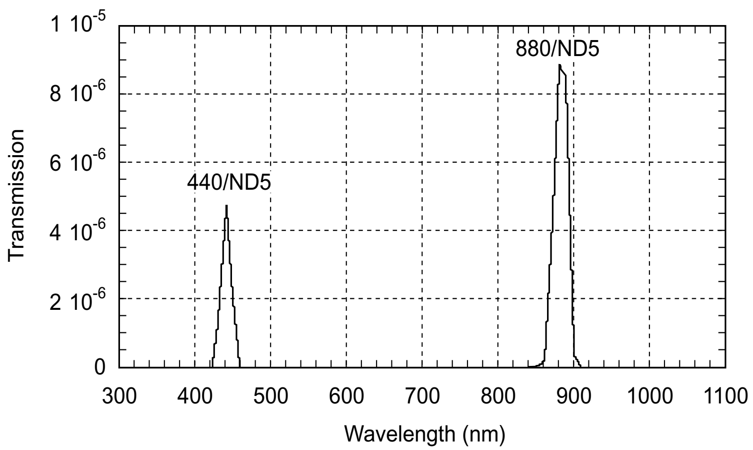
- **Common electronics design**
  - **FPGA controlled**
  - **Image integration times from 0 to 30 sec in steps of 5 ms**
  - **12 bit ADC**
  - **200,000 pixels/sec conversion rate**
  - **Frame transfer time ~ 5 ms**
  - **Full frame read time5.4 sec**
  - **4 x 1 pixel binning command**
  - **Partial frame read command—a set of adjacent rows**
- **CCD**
  - **Front side illuminated**
  - **Frame transfer type**
  - **1024 x 1024 pixel image and storage registers**
  - **12 x 12 µm pixels**
  - **Full well capacity < 150,000 electrons**
  - **Dark current < 1.5 nA/cm2 at 27° C and end of life (1.6 krad)**

Optics

- Custom designs optimized for the application
- Small, simple (minimum number of elements)
- Diffraction limited performance
- Large focal ratios (slow)
  - f/15 to f/20
  - Nominal 2 pixel diameter PSF @ 600 nm
- Spectral and/or ND filters
- Oversize elements eliminate vignetting and facilitate fabrication
- Operates at full performance from –55º C to 10º C
- Survives –120º C night time temperatures
- Lens Types
  - Pancam, MI, Navcam f-tanθ designs
  - Hazcam f-θ ultra wide angle (fisheye) design

Pancams

- Stereo pair
- 16x16º FOV
- 28 cm baseline
- On mast 1.2 m above the Martian surface
- Gimbal mounted
  - 360º azimuth capability
  - ±90º elevation capability
- Eight position filter wheel for multispectral imaging from 400 to 1100 nm
  - Science and engineering
  - Two narrow bandwidth ND 5 solar filters
    - One camera at 440 nm
    - One camera at 880 nm
    - Atmospheric spectral absorption and scattering
    - Sun Sensing
- Additional engineering functions
  - Stereo imaging
  - 3-D site characterization



Sun Sensing

- **Pancams provide Sun vector knowledge**
  - **Assist in determining rover attitude**
  - **Used for navigation and high gain antenna pointing**
- **Initial acquisition may require a gimbal search because of relatively small Pancam FOV**
- **Two axis data**
  - **Single image when Sun not near overhead**
  - **Two images when Sun near overhead**
    - **Fixed camera position**
    - **10 min apart**
    - **Sun moves by 2.5º**
- **Combined with accelerometer data on local vertical to derive 3-axis rover attitude knowledge**

Sun Centroiding

- Full Pancam CCD frame (taken with either solar filter) read out and stored in RAM
- During 5 sec readout time, worst case CCD dark current shading can be significant—subtracted from stored image
- Approx. 30x30 pixel window scanned over entire image and background of each window is calculated at each pixel location
- Background is subtracted from all pixels at each pixel location
- If the window location with highest value exceeds a preset threshold, the frame is identified as containing the Sun
- First centroid of Sun is calculated for highest value window
- Second centroid calculated for window that is centered on Sun

Navcam and Hazcam Configurations

Mars Exploration Rover

Navcams

- Navcam stereo pair mounted on the rover's mast assembly with the Pancams
- 20-cm stereo baseline and parallel optical axes.
- Best focus at 1000 mm.
- The Navcam's $45^\circ \times 45^\circ$ FOV sufficiently narrow to provide good stereo range resolution out to 30 meters and wide enough to efficiently provide 360° panoramas for traverse planning

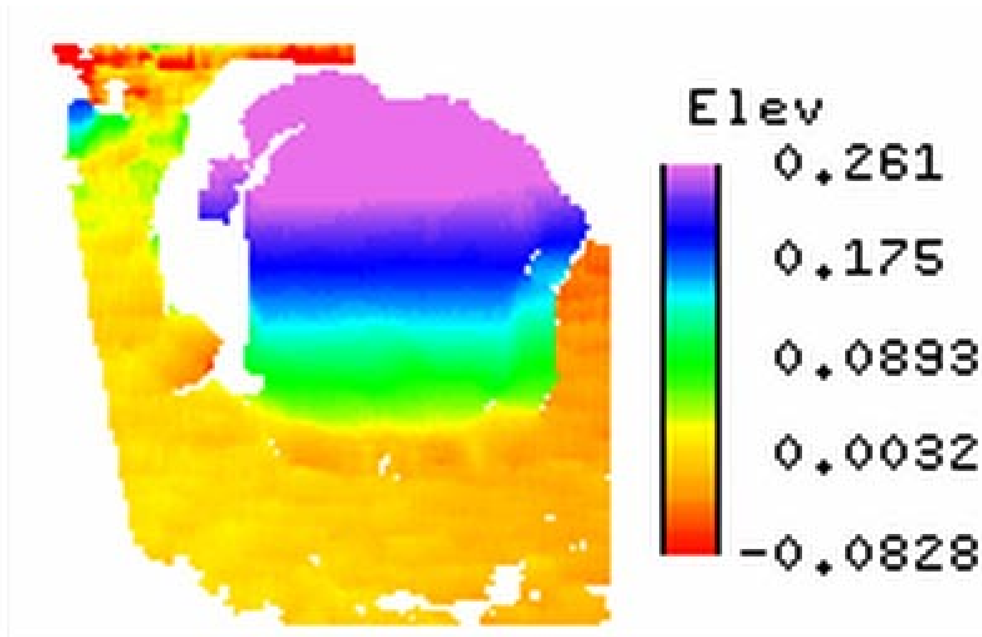
Hazcams

- Two pairs of Hazcams mounted on the front and rear of the rover ~50 cm above the Martian surface and pointed ~50º below horizontal
- 10-cm stereo baseline and parallel optical axes
- Best focus at 400 mm
- $127^\circ \times 127^\circ$ FOV provides nearby range data coverage
  - Area wider than rover
  - Good resolution to 3 meters

Stereo Vision Algorithm

- **Stereo camera pair (Navcams, Pancams, Hazcams) rigidly mounted to its camera bar**
- **Geometric camera lens pair model calculated from pre-launch image calibration**
  - **Precisely describes how coordinates in 3-D space map into the camera's 2-D image**
  - **Typical RMS projection error less than 0.2 pixels**
- **Image pair acquired from stationary rover**
  - **Image correlator applies 7 x 7-pixel window—evaluates potential matches for all pixels.**
  - **Matched pixels triangulated to generate a range estimate for every pixel**
  - **Unreliable range estimates automatically discarded—50–80% good range points per image typically remain**
  - **Range mapped into X, Y, Z positions in local rover coordinate frame**

Object Elevation Image



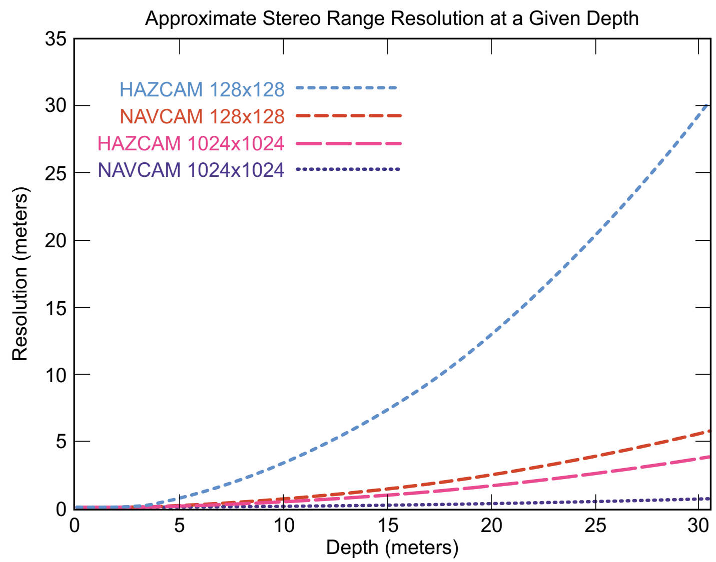
Boulder Image
(left image of stereo pair)

Elevation in meters

Stereo Vision Algorithm (cont.)

Mars Exploration Rover

- **Images from the Navcams and Hazcams ground can be processed at up to full 1024 × 1024-pixel resolution—best range resolution**
- **Image processed onboard at reduced 128 x 128-pixel resolution for local obstacle avoidance**
  - **Faster computation**
  - **~ 7,000 range points result**
  - **Higher resolution data not needed**
  - **Navigation system only needs data in 20 x 20-cm patches**



Range Data Use

Navcams

- **Acquire stereo grayscale panoramas**
- **Panoramas used by ground operators to plan rover's next day motion**
  - **Interesting targets are identified by their appearance or shape**
  - **Terrain model generated is used to plan the rover's motion toward them**

Hazcams

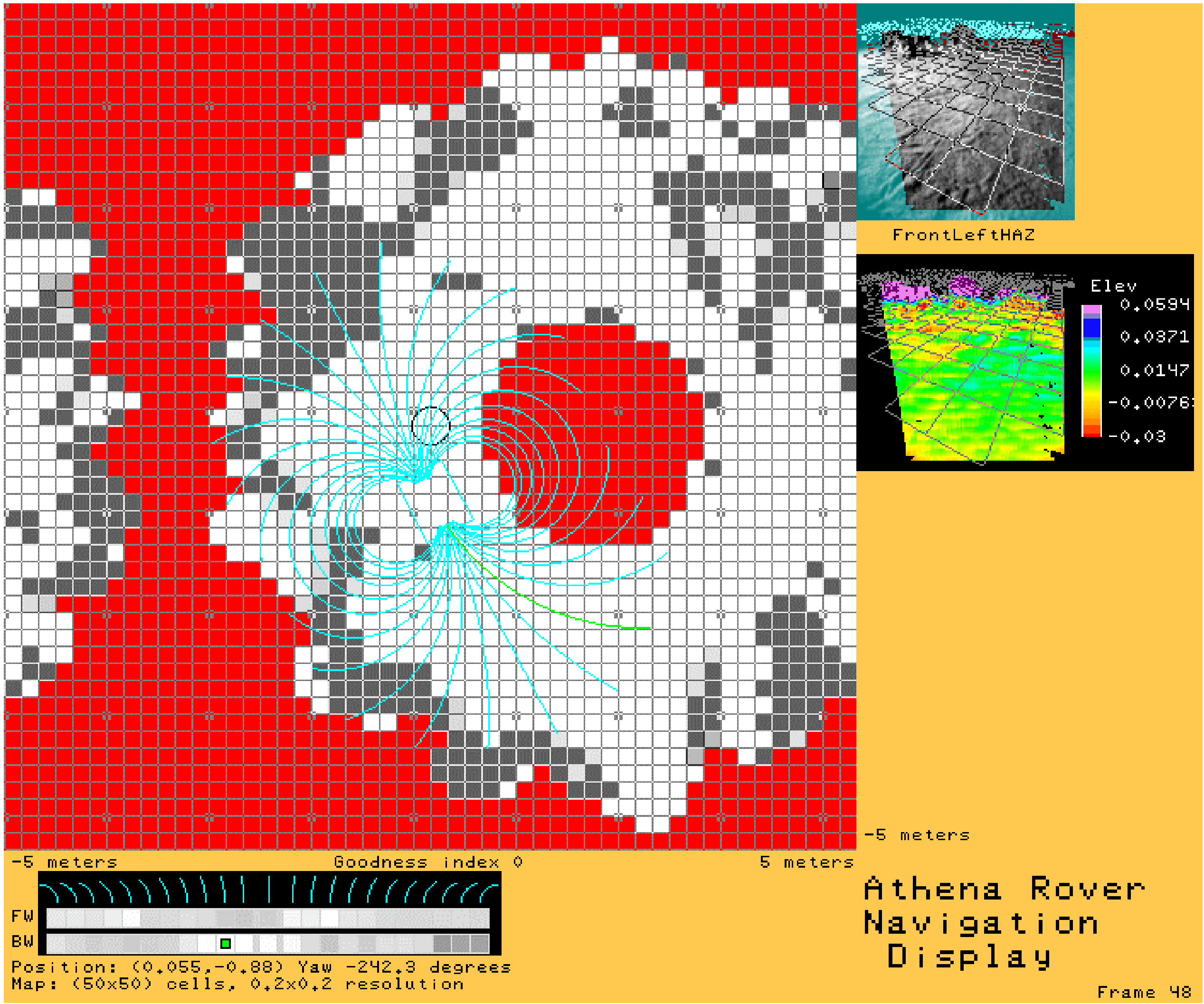
- **Primary range data use**
  - **Support nearby autonomous navigation**
  - **Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT) software package**
- **Secondary range data use**
  - **Plan operation of the Instrument Positioning System (IPS) with its extendible arm and science instruments**

GESTALT Algorithm

- Purpose—autonomously and safely drive rover through unknown terrain
- Models the terrain as a grid of regularly spaced cells
- Typical cell size a rover's wheel
- Traversability parameters computed for each cell
  - Slope
  - Residual
  - Maximum elevation difference
- Arc paths from current position evaluated by integrating traversability values from cells comprising the arc
- Arc with the highest evaluation is chosen as the next direction for the rover to follow

GELSTALT Navigation Map

Mars Exploration Rover



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Summary

- MER mission rover payload includes nine cameras
- Common electronics
- Unique optics for each type
- Provide scientific and engineering functions
- Microscopic Imager science only
- Pancam pair
  - Mostly science functions
  - Engineering function solar imaging to establish an inertially-based coordinate system
- Six additional engineering cameras mounted in stereo pairs (Hazcams and Navcams)
  - Autonomously generated range maps of the surrounding area
  - Obstacle detection and avoidance
  - Navigation
  - Ground traverse and Instrument Pointing System planning
  - General imaging